C&S RD&D Roadmap – 2005

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Codes & Standards Research, Development & Demonstration Roadmap

1.0 Introduction

The U.S. and most countries in the world have established laws, codes, and regulations that require products and facilities produced and used in transportation to be safe, perform as designed, and be compatible in systems use. Today hydrogen is produced and used in large-scale industrial and refining processes, but hydrogen has not been used as a commercial transportation fuel. To enable the commercialization of consumer-oriented hydrogen technologies, such as light duty vehicles, national and international codes and standards for hydrogen infrastructure and hydrogen fueled vehicles need to be developed and recognized and adopted by federal, state, and local governments.

Codes and standards primarily provide for public safety and include building codes, equipment standards, and automotive standards. Most U.S. codes and standards are developed by Codes and Standards Development Organizations (CDOs and SDOs, respectively)[1].

Locally responsible authorities (commonly referred to as the Authority Having Jurisdiction or AHJ) adopt codes to protect public safety in their jurisdictions or communities. Building and construction codes are familiar examples. Compliance is enforced by city and county building departments via permit reviews and field inspections. Likewise, State and Federal regulators adopt standards for products such as vehicles. Requirements for vehicle safety features are examples of Federal standards.

Some standards serve commercial interests by enabling products to be compatible with one another and to perform as expected. Common examples are standards that set frequencies used for radio communication, standards for compatibility of computer software, and the standard for 110-volt electricity in the U.S. Other standards serve both commercial interests and the protection of public safety. For example, standards that ensure the fueling nozzle at a gasoline pump will fit the fuel inlet of a gasoline (but not a diesel) vehicle also require safety features such as an automatic shut-off to prevent the fire hazard and environmental consequence of tank overfills.

Codes and standards often outline accepted performance requirements that guide the practices of businesses and industries. Requirements are often developed and modified based on experience gained by using products or technologies, or in the case of new products or technologies, on extrapolation of requirements for existing similar technologies. In some cases, experimental testing is used to develop requirements for new products or technologies, or validate requirements for existing ones. Because of the chemical and physical differences between hydrogen and other vehicle fuels currently in use, extrapolation of requirements from existing fuels is not fully appropriate or comprehensive. Similarly, the facilities, equipment, and personnel training associated with the industrial use of hydrogen are considerably different from what will be present for commercial "consumer" use. These issues make the role of Research, Development & Demonstration (RD&D) critical in the development of codes and standards for the widespread commercial use of hydrogen.

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[1] Refer to the Appendix for definition of terms, a listing of CDO and SDO entities, their scopes of coverage, and a generic description of code/standards development processes. The abbreviation "SDO" will typically be used interchangeably for either and both SDO or CDO throughout this document.

This Roadmap is a guide to the Research, Development & Demonstration activities that will provide data required for SDOs to develop performance-based codes and standards for a commercial hydrogen fueled transportation sector in the U.S. The contents of this Roadmap reflect the experience of and are subscribed to by the members of the FreedomCAR and Fuel Partnership (FCFP, or "the Partnership"), which include the U.S. Department of Energy (DOE), energy companies (BP America, Chevron Corporation, Exxon Mobil Corporation, Shell Hydrogen), and the U.S. Consortium for Automotive Research (USCAR) whose members include DaimlerChrysler Corporation, Ford Motor Company, and General Motors Corporation. The contents of this Roadmap will be reviewed and revised by the FCFP as needed to reflect changing needs and opportunities.

Recognizing the global similarity of transportation issues and objectives, this Roadmap is expected to have international relevance. Through an ongoing annual process of revising this Roadmap and evaluating specific needs for RD&D, an assessment of international efforts will be made to ensure new U.S. projects are efficiently leveraged and coordinated with those undertaken internationally. Through the International Partnership for the Hydrogen Economy (IPHE) the DOE anticipates creating alignment across an international field to help further individual country and collective global efforts in this arena. Information requirements of international SDOs will be considered to ensure alignment of RD&D projects with their needs for code and standard development.

The successful commercialization of hydrogen technologies and their integration into the transportation landscape requires that consumers will be able to use hydrogen and the related consumer technologies safely and conveniently. Robust codes and standards will provide that ability. This Roadmap lays out a research plan to collect, evaluate, and disseminate fundamental data in support of the development of safe, performance-based codes and standards within a timeline to enable industry to make a commercialization decision by 2015.

1.1 Objective

The objective of this Roadmap is to help establish an RD&D plan to achieve a substantial and verified database of scientific information on the properties and behavior of hydrogen, and the performance characteristics of new hydrogen technology applications that are sufficient to enable the development of effective codes and standards for emerging hydrogen applications. This information will be made available to appropriate SDOs, authorities and industry to enable the development of safe, performance-based technical codes and standards that will accommodate eventual changes in technology, thus minimizing the need to develop new codes and standards as technology evolves.

To meet this objective, additional fundamental studies are needed to build upon existing knowledge to understand the behavior of hydrogen and techniques for its safe handling in the anticipated commercial and consumer applications and environments. Components, subsystems and systems need to be subjected to operational and environmental conditions that replicate real-world use to validate their safe and effective operation. Various empirical data are also anticipated from DOE-initiated RD&D projects, including those that involve technology validation efforts.

This Roadmap is designed to support and accelerate the U.S. code and standard development process by identifying necessary RD&D in order to generate needed data and perform subsequent data analyses that will be made available to SDOs, industry and government authorities.

1.2 Background

The necessity for development of performance-based codes and standards to provide for public safety cannot be overstated. Further, the commercialization of hydrogen and related technologies will be slowed or perhaps prevented if the standards or model codes adopted are based on incomplete or incorrect data, or are design-specific.

The systems used to develop standards in various countries and regions around the world have developed and evolved over a long period of time, resulting in significant differences between them. In the U.S., standards are typically developed when a technology is near commercialization. The appropriate SDO is identified, and then industry provides the technical resources to develop the standard. This is usually a consensus-based process that is often time consuming. The data needed to establish the technical requirements may be limited, proprietary, or not validated to the level of confidence required by the SDO. When information is limited, standards may be written for expediency in design-specific, technology-based format and this can restrict or prohibit the later introduction of new technologies and designs. It is an objective of the FCFP, through this Roadmap, to outline a plan to develop comprehensive information and analyses to support the development of performance-based standards.

1.3 Approach

This Roadmap provides a pathway to ensure that the knowledge base for the development of codes and standards is comprehensive and sufficient. The development of the knowledge base for performance based codes and standards that ensure public safety and aid in commercial feasibility is two-pronged:

1. Through **Research and Development** (R&D), provide a comprehensive validation and understanding of the behavior of hydrogen, safety priorities, and technical capabilities involved in advancing the development of hydrogen codes and standards.

   Hydrogen properties differ from those of current commercial transportation fuels and its behavior must be understood to ensure hydrogen is produced, transported and used with systems designed, constructed, and operated to be safe.

2. Through **Demonstration**, validate the safe and convenient use and handling of hydrogen in vehicles and infrastructure processes and equipment.

   Demonstration and validation provide key elements in assuring that safety and performance objectives are realistic. Demonstration of technologies verifies expected performance and resilience to use under an assortment of unpredicted conditions and applications. Demonstration of technologies for purposes of developing codes and standards differs from demonstration of technologies in early development. The latter is designed to reveal performance deficits, and thereby guide the next stage of R&D for design modification. Demonstration needed for codes and standards aims to verify commercially viable performance, durability, safety, and also provides local officials with real-world compliance experience.

   Validation consists of testing in laboratories, and reliable and durable performance in real-world usage. Validation includes the accumulation of sufficiently extensive real-world experience and data to verify with statistical confidence that expected performance is reliably achieved. As technologies advance toward designs assessed to have significant potential for commercialization, validations include the deployment of test infrastructure facilities, vehicle fleets and refueling facilities to attain sufficient real-world experience that can also act to establish the basis of public confidence.

1.3.1 Process

The process necessary to execute the objectives identified above consists of the following sequence of steps:

1. Identification of **Information Needs** within an organized framework (see Section 2.0 Work Plan)

   As detailed in Section 2.0 below, the overall effort has been categorized into four (4) focus areas that consider assessment of current practices and the status of technical standards development efforts, both nationally and internationally. Each category will have Information Needs (or gaps) identified relative to current efforts, existing data and analyses, and existing codes and standards needed to support safe consumer use of hydrogen.

2. **Prioritization** of Information Needs based upon safety, dependencies, and criticality, as reflected in the Roadmap Deliverables Timeline. An initial Deliverables Timeline is shown in Figure 1; however, prioritization will be revisited annually.

   To consider both the safety and timing aspects that impact codes and standards needed for commercial hydrogen development, prioritization will be accomplished using a protocol that adapts techniques derived from scenario analysis, risk assessment and critical path analysis methodologies.

3. Determination of whether the Information Needs will be best resolved via **R&D** or **Demonstration approaches**.

   Information Needs best resolved utilizing **R&D and experimentation approaches** will be areas involving understanding hydrogen behavior and validating simulation models, which will be used to confirm and augment technology demonstrations and validations. Through the development and validation of these tools, supporting analyses using predictive models for hydrogen behavior can be performed. Additionally, basic technology performance requirements and technical capabilities may also be suited to an R&D-type approach (e.g., hydrogen quality).

   Information Needs best resolved utilizing **Demonstration approaches** will be areas involving "ready-to-validate" technologies that are mature with regard to meeting performance requirements, durability and reliability. It is important to avoid expending limited resources investigating interim gaps that may be relevant only to "demonstration-ready" technology but that will not be relevant to anticipated "commercial-ready" technology.

4. Support of definition and execution of specific **Projects** that can resolve the Information Needs and communicate and report results within the program timeframe.

   Projects will include data collection from R&D and technology demonstration and validation projects, data analysis, and safety verification based on modeling of hydrogen behavior. Projects may also include basic R&D and Testing.

5. Support of annual **review** of DOE-funded RD&D projects related to codes and standards through participation in the merit review process and other review opportunities. Following review of the projects, the Roadmap will be assessed for potential changes to align future projects to meet the necessary goals.

6. Review and create a mechanism to **disseminate pertinent information** to appropriate SDO bodies and ensure the Roadmap reflects an awareness of ongoing activities by these bodies.

   As the data are validated, they will be provided to SDOs as these bodies further develop and maintain consensus-based technical codes and standards.

2.0 Work Plan

This Roadmap begins with and includes an ongoing assessment of the sufficiency and optimization of hydrogen and fuel cell codes & standards that are established and in the process of being established domestically and internationally. This Roadmap is designed to identify and resolve Information Needs (gaps) related to those codes and standards for a hydrogen-based transportation system. Following the process outlined above, RD&D projects will be reviewed and additional Information Needs identified to address gaps and provide documented research to SDOs, on a continuing basis.

2.1 Roadmap Organization

The Roadmap is organized into four Focus Areas:

1. Hydrogen Behavior
2. Hydrogen-fueled Vehicles
3. Hydrogen Fuel Infrastructure
4. Fuel-Vehicle Interface

The technical goal for each of these Focus Areas is to gather sufficient information and validating experience on technology applications so that the responsible SDO can proceed. Each Focus Area is subdivided into key Target Areas which identify important Information Needs and aspects, for which SDOs require information to fully develop codes and standards.

The completion of RD&D for the individual technical Target Areas, in conjunction with information distribution, is expected to result in the subsequent development of safe, performance-based codes and standards by SDOs.

Codes & Standards Focus Areas

Hydrogen Behavior	Hydrogen Fuel Infrastructure	Fuel-Vehicle Interface	Hydrogen Fueled Vehicles
<u>Key Target Areas</u>	<u>Key Target Areas</u>	<u>Key Target Areas</u>	<u>Key Target Areas</u>
• Physical properties	• Production	• Fueling nozzle & protocol	• Onboard hydrogen storage
• Flammability	• Distribution & Delivery	• Fuel quality	• Onboard fuel handling
• Material compatibility	• Refueling Station	• X-cutting issues	• Parking requirements
• Detection			

Presently, more detail is included for the Hydrogen Behavior Focus Area, since DOE has had significant RD&D efforts underway for some time. The fundamental data generated and analyzed in this Focus Area serve as a critical reference for the other Focus Areas and related Target Areas. Revisions to this Roadmap are expected to expand the focus on hydrogen technologies and to reflect changes in direction as new Information Needs are identified.

2.2 Timeline and Milestones

To enable industry to make a commercialization decision in time to meet the FreedomCAR and Fuel Initiatives' goal of bringing hydrogen-powered vehicles to market by 2020, it will be necessary to have codes and standards in place no later than 2015. Working backwards from the 2015 codes and standards target date, SDOs will need sound, verified data by approximately 2010, so that appropriate standards can be developed and institutionalized. In addition, parallel efforts to develop Global Technical Regulations by 2015 are also considered in the development of the overall timeline.

RD&D Roadmap Timeline (2005)

"Completed By" dates shown

Category	Information Need Areas	2005	2006	2007	2008	2010
Hydrogen Behavior	Properties	©				
	FVC Formation, LFL		©			
	Jets and Flames		©			
	LH_2 Releases			©		
	Materials Compatibility			©		
	Metal Hydride Materials, Behavior				©	
	H_2 Sensors				©	
Hydrogen Vehicle	H_2 Tank Testing		©			
	H_2 Refueling Tests			©		
	Life-cycle Testing					©
	P-Relief Devices			©		
	P-T Sensors			©		
	On-board fuel handling				©	
	Parking Certification			©		
Hydrogen Infrastructure	At-scale H_2 data			©		
	Quality: Prod - Nozzle				©	
	Mitigation/Detection				©	
	Pipelines					
	Materials Assessment			©		
	Nondestrct Eval Meth				©	
	Failure Modes		©			
	Existing CNG Infra		©			
	High P Composite Mat			©		
	Embrittlement			©		
	Fuel Measurement					©
Fuel-Vehicle Interface	Fuel Quality : Nozzle – Fuel Cell				©	
	Feedback Strategies			©		
	Dispenser Protocol and Testing				©	
	Fueling Components				©	
	Station Grounding		©			
	Integrated Engr-Design					©
R&D Approach	Scenario Analysis	©				
	Risk Assessment/CPM	©				

2015: Final Code Development Period (2010 – 2015) to meet Commercial-ization Decision of 2015

Target all information to be shared to SDOs by 2010

Figure 1: High-level Milestones and Relationship to Target Areas.

2.3 Focus Areas

2.3.1 Hydrogen Behavior

The development of a comprehensive, verified, and validated database is a necessary element for the establishment of safe, performance-based codes and standards for widespread use of hydrogen and hydrogen technologies. These data are essential to develop accurate predictive models, including the effects of hydrogen on innovative and conventional materials.

Within this section several Information Needs are identified which can help ensure achieving the codes and standards milestones set forth within this Roadmap.

2.3.1.1 Physical and Chemical Properties

Accurate equations for computer-based simulation models relating the chemical and physical properties of hydrogen under various environmental conditions will be required to predict the behavior of hydrogen in “real-world” situations. A thorough review of the literature is needed to assess the accuracy of engineering models and sufficiency of thermodynamic, transport and combustion properties of liquid and high-pressure hydrogen. RD&D projects will be developed to provide the missing data, verify historical information, and clarify misinterpretations related to hydrogen behavior.

2.3.1.2 Combustion and Flammability

Accurate and comprehensive information on circumstances under which hydrogen could ignite and characteristics of its combustion must be acquired and made publicly accessible. Experimental verification of literature values and generation of additional data are also needed. In addition, accurate heat transfer correlations are required to model the effects of hydrogen flame impingement and heat fluxes from an ignited jet or combustible cloud. Understanding the behavior of hydrogen combustion events is essential for assessing and avoiding potential adverse impacts.

The capability to characterize the mixing of the hydrogen with ambient air in jets and dispersed flows of varying velocities and duration (quantity) and in confined, semi-confined, and unconfined spaces is needed to predict potential impacts. Investigation of ignition characteristics and sources under realistic conditions needs to be performed.

The potential for radiant heat transfer from the flame to the surroundings, under varying conditions, needs to be assessed. An understanding of the radiative properties of jet flames and a capability to predict radiative heat flux for a given flame will be critical to effective risk management.

Accidental releases of liquid hydrogen from underground and aboveground storage containers could result from storage tank failure or accidents involving transfer or transport of bulk hydrogen. Ignition studies of liquid hydrogen pools and the surrounding flammable vapors are needed. An understanding of hydrogen handling and use is necessary to identify what mitigation efforts can be implemented to minimize the potential hazards.

Potential experimental projects for characterization of jet flame and combustible cloud behavior may include:

- Laminar and turbulent jets and flames
- Flammable cloud formation, dispersion, dynamics and ignition
- Liquid hydrogen releases
- Flammability of buoyancy-driven flows
- Real-world lower flammability limit in enclosed spaces

Experimental projects are needed to develop and validate mathematical models used to predict impacts of unintended releases. Information on the proposed projects for characterization of jet flame and combustible cloud behavior is summarized in the Appendix.

2.3.1.3 Material Compatibility

Existing data on compatibility of materials with hydrogen need to be compiled from reports and journal publications. The effects of hydrogen on yield and tensile strength, fracture toughness and threshold stress-intensity factor, fatigue crack growth rates and fatigue thresholds need to be understood to ensure the safe design of components (e.g. pressure tanks, piping, and valves). Creep rates and creep rupture strength are important in the design of components exposed to temperature extremes. Hydrogen permeation rates are needed to quantify the amount of hydrogen that might penetrate through boundaries in contact with hydrogen gas, and subsequently break down the structure of the material. The temperature/pressure relationship is also an important factor that will need to be quantified as it applies to hydrogen permeation. In addition, impact on system components as a result of fuel impurities, such as water, hydrogen sulfide, and trace acids need to be assessed.

The effect of hydrogen on the mechanical properties of some materials (for example, polymers and composites) has not been extensively investigated. Permeation of hydrogen through solid polymer boundaries is of particular interest, since the structure of polymers is dramatically different compared to metals. Existing data on the hydrogen compatibility of polymers and composite materials exposed to hydrogen gas environments need to be identified and evaluated.

As the literature search progresses and missing data are identified, materials testing needs to be conducted to fill the data gaps. Based on a preliminary review of literature data, initial experiments need to be conducted on statically loaded metals in high-pressure hydrogen gas to measure crack growth rates and threshold stress-intensity factors. Pressures need to be determined based on likely system design and, where available, using industry safety factors. These data are essential in defect-tolerant design of load-bearing structures in hydrogen gas environments. In addition, experiments on metals subjected to fatigue, i.e., cyclic loading in high-pressure hydrogen gas, need to be conducted to measure crack growth rates and thresholds for fatigue crack propagation.

2.3.1.4 Detection

Although safety-by-design and passive mitigation systems are the first option, it will be necessary to develop technologies to detect hydrogen releases. The development of fast-response, high-sensitivity, accurate hydrogen sensors for leak detection will help establish public confidence. Also, the effectiveness of mitigation strategies will require verification by experiments, model simulation and real-world validation. The accuracy, reliability, and durability of sensors under real-world conditions as well as sensor technology, design, and placement options and strategies need to be assessed.

Requirements and design options for innovative hydrogen detection technologies need to be evaluated. Feasibility assessments of technologies and analytic techniques for wide-area and remote sensing of hydrogen need to be conducted. Such assessments could include low-cost sensor arrays, specifically addressing the transfer of instrument calibration between devices and the stability of devices over time. Further, the application of gettering polymer films and gasket materials for coating onto pipe and applying between joined surfaces may be another area to assess. Potential detection requirements and techniques to assist first responders to accidents also need to be assessed.

2.3.2 Hydrogen Fueled Vehicles

Safety is an important issue associated with the introduction of hydrogen-fueled vehicles. Automotive standards exist today to ensure production vehicles perform as designed and meet regulations for safe operation. This Roadmap emulates past approaches when new transportation technologies (electric vehicles, CNG) were introduced. Existing vehicular standards will be used where appropriate, and new standards will be developed as needed, for any new technologies being implemented. This section focuses on the RD&D required to obtain safety-related data for onboard hydrogen storage systems that will be needed to develop performance-based standards.

On-road experience provided from various DOE-funded validation projects will be useful in validating performance of prototype designs in this area.

Within this section several Information Needs are identified which can help ensure achieving the codes and standards milestones set forth within this Roadmap.

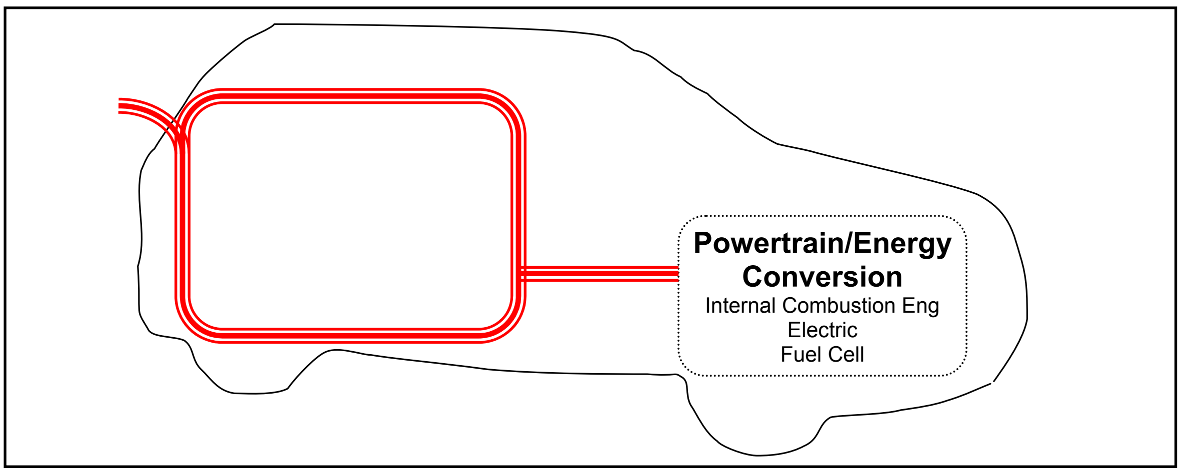

Figure 3. Codes & Standards focus for hydrogen-fueled vehicles is the onboard hydrogen storage system.

2.3.2.1 Onboard Hydrogen Storage System

The unique structural characteristics of the hydrogen-fueled vehicle will focus on the onboard hydrogen storage (tank or other media) and hydrogen delivery systems. This Roadmap will accommodate all forms of hydrogen storage (such as high pressure, liquid, lower pressure or chemically bound hydrogen, etc.) as each technology progresses toward potential commercial feasibility. Materials used for the system need to be defined and modeled appropriately. Exposure to static electricity and other ignition sources during normal and abnormal conditions need to be evaluated, including electrostatic discharge studies, and appropriate testing needs to be performed.

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2.3.2.1.1 Hydrogen Storage Tank Testing

The properties (mass, stiffness, geometry) of the fuel storage, connectors and delivery system are crucial to the integrity and safety of the system. Compressed hydrogen storage tanks and associated fuel lines need to be evaluated, giving due consideration to the effect of internal pressure, operating temperature and the material properties over thousands of filling cycles.

As with contemporary vehicles, the analysis of impacts needs to consider the potential impingement of surrounding structure upon the fuel storage tanks.

Ultimately, standards for hydrogen storage will specify performance-based tests that storage systems would be required to satisfy. These performance tests will likely differ for compressed hydrogen, liquid hydrogen, chemically bound hydrogen, and hydrogen contained within solid-state media.

2.3.2.1.2 Hydrogen Storage Refueling Tests

At present, testing requirements for compressed hydrogen storage systems have been based on comparably pressured onboard storage of natural gas. Particularly for compressed systems, refueling requirements need to be explored and evaluated for all types of tanks, in order to safely achieve optimized fills for different storage tank working pressures, with focused attention to burst pressure, over-pressure and creep temperature.

2.3.2.1.3 Life Cycle Testing

Initially, known potential life cycle issues will be explored: 1) durability of compressed hydrogen storage tanks with repeated exposure to temperature extremes, 2) impact of hydrogen fuel quality on hydrogen storage durability, and 3) lifetime durability of tanks exposed to numerous refueling events. As additional life-cycle issues emerge, elements will be added to this RD&D Roadmap.

Existing high-pressure tank standards have upper limits on the temperature of the bulk gas. This temperature limit requires that fill rates be set so that the gas temperature does not exceed design temperatures. Studies are required to understand the impact of high temperatures on refueling-cycle reliability for the full spectrum of compressed storage tanks, including material issues related to the limits of creep.

Life cycle testing will also focus on the impact of hydrogen fuel quality (water and particulate content) on the durability of compressed hydrogen storage tanks, with particular attention to valves and gasket erosion. The impact of fuel quality on solid-state storage media will be evaluated once the development of these advanced storage systems meets performance targets.

2.3.2.1.4 Pressure Relief Devices

Pressure Relief Devices (PRDs) provide a safety mechanism for overpressure of compressed hydrogen storage systems. Therefore, a comprehensive and systematic evaluation of PRDs under foreseeable operating conditions is needed.

2.3.2.1.5 Pressure and Temperature Sensors

Pressure and temperature sensors need to be developed that are compatible with the storage system. Performance measures of importance include reliability, dynamic accuracy, response time, and lifecycle cost. Analysis is needed to identify the appropriate requirements for these sensors. Research and development activities need to subsequently target development of appropriate sensors to address all identified modes of operation and all expected environmental conditions.

2.3.2.2 Onboard Fuel Handling

Compressed hydrogen storage systems will use pressure regulators to reduce the pressure of the hydrogen for delivery to the fuel cell power system. Research to explore and document the temperature limits of pressure regulator designs, particularly with regard to hydrogen fuel quality (water and particle content), is needed.

2.3.2.3 Parking requirements

Hydrogen-fueled vehicles may require certification for safe use in parking structures. This is accomplished for natural gas vehicles by the establishment of a test method for vehicle certification for parking those vehicles indoors. Research is needed to develop a similar certification for hydrogen-fueled vehicles. A potential certification criterion may need to be established (e.g. leak rate, etc.).

2.3.3 Fuel Infrastructure

A variety of feedstocks and processes, at various scales, are being considered for the production of hydrogen, and its use as a transportation fuel. Each technology is in a different stage of development and each offers different challenges. This includes all of the requirements for central and distributed systems, the transport of hydrogen under the Code of Federal Regulation, zoning issues related to the manufacture of hydrogen at refueling sites, bulk storage setback and permitting related to local ordinances.

Within this section several Information Needs are identified which can help ensure achieving the codes and standards milestones set forth within this Roadmap.

2.3.3.1 Production

Large central hydrogen production plants are common and have been built and individually permitted as industrial sites. Industrial-scale hydrogen production is well understood from a codes, standards, and industry practice standpoint and is therefore not generally considered within the scope of the RD&D needs for hydrogen production. However, should a distributed-type production approach be contemplated for widespread use, efficient smaller scale distributed systems will require the ability to use commercially mass-produced equipment such as reformers, shift converters, electrolyzers, and purification equipment. Common equipment for all of the production processes may include high-pressure compressors, coolers/chillers, quality assurance instruments, monitoring and/or sensing devices, and various storage systems depending on pressure and state of the hydrogen.

While industrial production methods and practices are well understood and codified, most industrial requirements are either inappropriate for wide-spread use in consumer environments or are perhaps too restrictive, as many are based upon very large scale processes as compared to what might be anticipated for consumer settings. Therefore, identified gaps that could be resolved through RD&D, in support of consumer-scale production applications, include:

2.3.3.1.1 Hydrogen Behavior Data for smaller-scale retail and consumer applications

Comprehensive data regarding hydrogen behavior relative to the anticipated smaller scale retail and consumer applications are needed. A significant portion of the required and supportive RD&D is addressed within the first section of this Roadmap, section 2.3.1 - Hydrogen Behavior. However, while the effort will provide relevant empirical and modeled data, additional RD&D to quantify the hazard relative to the scale of retail and consumer applications is necessary. Approaches to this effort might include scenario analyses, risk assessments and/or experimentally generated data from production mock-ups to identify and analyze the potential hazards of these facilities. Instead of having to extrapolate hazard information and existing code requirements developed from/for larger industrial/commercial facilities, SDOs will be able to use these hazard data directly to write code language suitable for smaller-scale applications.

2.3.3.1.2 Hydrogen Quality

A comprehensive understanding of hydrogen quality issues related to hydrogen production methods and the respective clean-up systems is needed. Industry-available research results in this area will help in further defining hydrogen supply system requirements and help establish commercial standards for the industry.

2.3.3.1.3 Mitigation & Detection Strategies

A need exists to determine the most effective methods for identifying "safety by design" approaches to mitigate potential unintended hydrogen releases and/or detection methods using various sensor-type technologies. Additional details related to this area can be found in Sub-section 2.3.1.4 Detection.

2.3.3.2 Distribution and Delivery - Pipelines

The existing, limited commercial infrastructure is not sufficiently developed to meet the requirements if hydrogen is to be used as a consumer transportation fuel. Options for the delivery from central and distributed systems have not been fully analyzed. Most of the data needed for this analysis have not been developed but will be provided under Section 2.3.1. – Hydrogen Behavior.

It is possible that terminals will be used to supply hydrogen to distributed markets for transportation and stationary applications. The technology for the transmission of hydrogen from large central processing facilities may be different from localized distribution systems. This may include liquids, slurries, carriers, and solid-state methods, which may be converted for local use. The Distribution and Delivery scope includes activity outside the plant/refinery gate to move product to the retail end-point. Plant/refinery gate activities are considered industrial-scale and already addressed by existing code.

Information Needs for Distribution and Delivery are presented within the subsections listed below:

2.3.3.2.1 Pipeline Materials Assessment

A comprehensive understanding of the performance requirements for metallic and non-metallic systems through materials assessment is needed. Data generated in the efforts supported in Sub-section 2.3.1.3 – Material Properties and Compatibility, will also address this specific area of application.

2.3.3.2.2 Non-destructive Evaluation Methods

A need exists to determine appropriate non-destructive testing (NDT) methods for hydrogen pipeline applications such that industry practice can be efficient and consistent.

2.3.3.2.3 Predicted Failure Modes and Component Failure Rates

It is necessary for industry and SDOs to have a common understanding of predicted failure modes due to rapid pressurization and temperature of components and subsystems involved in pipeline applications, including materials and component failure rate data for various elements (e.g. pressure relief devices).

2.3.3.2.4 Mitigation & Detection Strategies

Refer to Section 2.3.1.4 for more information.

2.3.3.2.5 Hydrogen Quality

A comprehensive understanding of hydrogen quality issues related to distribution and delivery systems is needed. Research results in this area will help in further defining the hydrogen supply system requirements and in identifying quality assurance practices, and will help establish practical commercial standards for the industry.

2.3.3.2.6 Existing Natural Gas Distribution Infrastructure

There are disagreements among experts on the material and functional compatibility of using the existing natural gas distribution infrastructure for gaseous hydrogen. Research and evaluation is needed to resolve this question.

2.3.3.3 Distribution and Delivery -Terminals

(Common Information Needs as identified in Pipelines above and Bulk Transport below)

2.3.3.4 Distribution and Delivery - Bulk Transport (includes: delivery trailer, rail, ship, barge)

Most Bulk Transport Information Needs are similar to those identified for Pipelines and Terminals and therefore are not restated herein. However, some additional Information Needs are further defined below:

2.3.3.4.1 Composite Materials for High Pressure Storage

Similar to Materials Assessment identified under Pipelines, a need exists to understand the performance of these type vessel solutions in large scale applications associated with Bulk Transport.

2.3.3.4.2 Embrittlement

Ensure Sub-section 2.3.1.3, Material Properties and Compatibility, addresses Bulk Transport related applications (e.g. piping, valves, storage).

2.3.3.4.3 Component Performance Requirements

Understanding the capabilities of available components against a database of performance requirements (e.g. backflow preventers, PRDs, rupture disks, safety factors).

2.3.3.5 Refueling Stations

Current state-of-the-art hydrogen refueling stations are demonstration projects that are based on scaled-down versions of industrial practice and are typically required to adhere to existing industrial codes and standards. Future refueling stations will likely involve the use of a variety of forms of hydrogen, including; high-pressure gas, ultrahigh-pressure gas, cryogenic fluid, liquid carriers of hydrogen, etc. These facilities may be designed to produce hydrogen on-site via reforming, electrolysis, or other conversion processes, and will store hydrogen using pressure vessels of various materials, cryogenic vessels, or low-pressure vessels incorporating potentially pyrophoric materials. Each station may involve various production and storage size requirements. Placement of these components may involve below-grade (vaulted or direct bury), ground level, or overhead installations. Piping and dispensing systems will need to provide various pressures using standardized procedures and hardware.

Most Refueling Station Information Needs are similar to those previously identified for Production and Distribution and Delivery and therefore are not restated herein. However, some additional Information Needs are further defined below:

2.3.3.5.1 Risk Based Modeling and Hazard Assessments

A need exists to connect the data obtained from Section 2.3.1, Hydrogen Behavior, to the applications to be deployed at the scale expected for refueling stations. An understanding of the relative risk and hazard associated with the refueling station application is important to effective code development.

2.3.3.5.2 Measurement

Accurate measurement and commercial transaction capability of hydrogen at high pressure or in cryogenic form is needed. Ideally, the accuracy should be equal to current practice with retail sales of gasoline. SDOs and regulatory officials need to develop and/or understand the consistency and accuracy of measurement approaches when writing standards or executing the regulation. This work will be tied back to Sub-section 2.3.1.1, Physical and Chemical Properties, and will make use of data and expertise available at NIST.

2.3.4 Fuel-Vehicle Interface

This focus area addresses the fuel-vehicle interface, including those requirements for hydrogen-fueled vehicles and refueling stations to ensure safe consumer interaction and use of hardware and systems. This particular interface includes the dispensing nozzle and equipment on-board the vehicle, feedback strategies, fuel weights and measures, and approaches to prevent pressure relief device activation or failure. Empirical results from demonstration and validation programs will be included in the analysis of requirements for safe refueling of hydrogen vehicles.

In addition to safe vehicle refueling, the fuel-vehicle interface focus area includes analysis of cross cutting issues and RD&D for potentially innovative solutions, such as integrated systems approaches to safe design and operation. This focus area will also identify in a systematic way potential unintended hydrogen release events, particularly at the fuel-vehicle interface. Auto OEMs and energy companies will identify potential hydrogen release events involving vehicles and the fuel infrastructure, respectively, to aid in prioritization as described in Section 1.3.1.

Within this section several Information Needs are identified which can help ensure achieving the codes and standards milestones set forth within this Roadmap.

2.3.4.1 Hydrogen Fuel Quality

Fuel quality needs to be quantified at the vehicle/station interface, as it affects the onboard fuel cell and hydrogen storage, and it is where the output of the station (the fuel) first encounters the vehicle. This will require testing to determine the effects of various impurities on fuel cell electrodes and membranes. In addition, impurity effects on the onboard fuel system need to be investigated. The impurities to be tested need to be based on the combination of all possible contaminants that can affect the vehicle systems and that could be delivered from the fuel infrastructure systems. Other items subject to the investigations into fuel quality are:

- Identification and classification of impurities
- Protocols to test effects of impurities
  - Detection and analysis of impurities
  - Procedures to measure and report effects
- Degradation mechanisms of fuel impurities
- Implications of hydrogen fuel quality for complexity, performance and durability of fuel cell systems and upstream hydrogen infrastructure

2.3.4.2 Feedback Strategies

Feedback strategies apply to physical couplings, electrical connectors, etc., that prevent hydrogen-fueled vehicles from being fueled with service pressures higher than the vehicle allows, while permitting hydrogen vehicles to be fueled with service pressures equal to or lower than the vehicle fuel system service pressure. These strategies can also prevent hydrogen-fueled vehicles from being fueled with other compressed gases, and vice-versa. Additional benefits from communication or feedback strategies can be the detection of insufficient sealing, fill-rate control, wear and tear, etc.

Evaluation is needed in the area of communication and "feedback" strategies, (which involves inherent design elements for "safety-by-design" feedback), hardware and electrical componentry to understand the most safe and effective approaches to refueling vehicles.

2.3.4.3 Dispenser refueling protocols and testing

As stated in onboard vehicle storage, it is critical to establish refueling protocols that meet requirements for safety and for optimizing the quantity of hydrogen received in vehicle storage. RD&D is needed to develop design alternatives that allow the vehicle to safely achieve fill requirements. Fill rate and other requirements will need to be ascertained through understanding system and component capabilities. Inherent fill protocols-by-design are also needed which can provide for safe and efficient fills.

2.3.4.4 Refueling Hardware

Designs for hydrogen fueling hardware depend on the form of hydrogen delivery (high-pressure gas, liquid, or chemically bound hydrogen in solids or slurries). Redesign of equipment is proceeding rapidly as deficiencies in consumer convenience, cost, and utility are addressed.

Key areas of evaluation include the identification and resolution of consumer safety issues for the station-to-vehicle interface, which involve:

- Development of high pressure nozzle/receptacle test requirements
- Development or validation of hydrogen hose (pressurized, liquid, other) test requirements.
- Development or validation of hydrogen hose-breakaways test requirements.
- Specialized test fixtures and chambers to evaluate equipment designs for durability, reliability and safety.
- Testing requirements to validate refueling systems -- coordinated with NIST.

2.3.4.5 Station Grounding

In order to ensure refueling and storage safety, it is important that there is electrical continuity between the ground and the refueling system, including components such as dispenser, dispenser nozzle, vehicle, vehicle pad, and delivery hose. This is especially important at locations where system connections are made and broken, and where a flammable mixture may be present, such as the vehicle and station interface. A comprehensive study to explore grounding conditions and requirements is needed.

2.3.4.6 Integrated Engineering and Design Approaches

An integrated engineering approach is needed to ensure that components and subsystems meet technical requirements incorporated in key hydrogen standards. Such an approach will assess whole system requirements for active and passive technologies, buildings, and facilities and explore design options to meet technical requirements. Innovative approaches, such as advanced sensor technologies and the incorporation of sensor technologies in storage tanks, smart PRD designs, and tracers for hydrogen gas leak detection will be explored. Case studies need to be conducted to assess current technologies and capabilities to meet existing safety requirements.

APPENDIX - 1

FOCUS AREA / TARGET AREA: added detail, review information, developments

Format: A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.1 Hydrogen Behavior

2.3.1.1 Physical and Chemical Properties
2.3.1.2 Combustion and Flammability
2.3.1.3 Material Properties and Compatibility
2.3.1.4 Detection and Mitigation

2.3.2 Vehicle

2.3.2.1 Onboard Hydrogen Storage System
2.3.2.2 Onboard Fuel Handling
2.3.2.3 Parking Requirements

2.3.3 Fuel Infrastructure

2.3.3.1 Production
2.3.3.2 Distribution and Delivery - Pipelines
2.3.3.3 Distribution and Delivery - Terminals
2.3.3.4 Distribution and Delivery - Bulk Transport
2.3.3.5 Refueling Station

2.3.4 Fuel-Vehicle Interface

2.3.4.1 Hydrogen Fuel Quality
2.3.4.2 Feedback Strategies
2.3.4.3 Dispenser Refueling Protocols and Testing
2.3.4.4 Refueling Hardware
2.3.4.5 Station Grounding
2.3.4.6 Integrated Engineering and Design Approaches

2.3.1.1 Physical and Chemical Properties Appendix

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.1.2 Combustion and Flammability Appendix

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.1.3 Material Properties and Compatibility Appendix

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.1.4 Detection and Mitigation Appendix

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.2.1.1 Hydrogen Storage Tank Testing Appendix

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.2.1.2 Hydrogen Storage Refueling Tests Appendix

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.2.1.3 Life Cycle Testing Appendix

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.2.1.4 Pressure Relief Devices Appendix

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.2.1.5 Pressure and Temperature Sensors Appendix

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.2.2 Onboard Fuel Handling

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.2.3 Parking Requirements Appendix

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.3.1 Production Appendix

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.3.2 Distribution and Delivery – Pipelines Appendix

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.3.3 Distribution and Delivery – Terminals Appendix

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.3.4 Distribution and Delivery – Bulk Transport Appendix

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

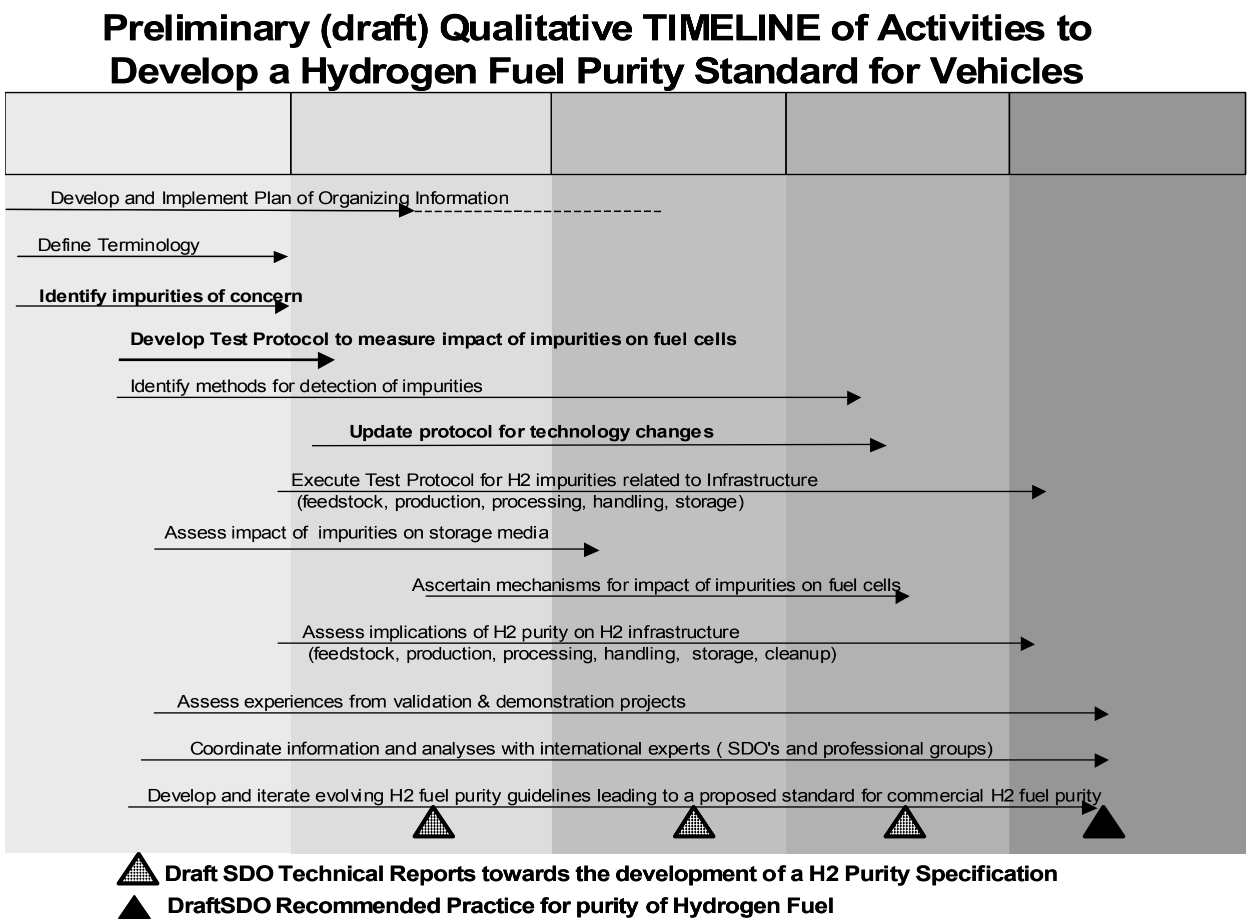
2.3.3.5 Refueling Station Appendix

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.4.1 Hydrogen Fuel Quality Appendix

A) Milestone Timeline

A timeframe for achieving the qualitative key elements of the R&D Roadmap for a potential hydrogen fuel quality specification is illustrated in the following.



B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.4.2 Feedback Strategies Appendix

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.4.3 Dispenser Refueling Protocols and Testing Appendix

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.4.4 Refueling Hardware Appendix

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.4.5 Station Grounding Appendix

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

2.3.4.6 Integrated Engineering and Design Approaches Appendix

A) Milestone Timeline
B) Project Detail
C) Review Comments
D) Timeline Assessment

APPENDIX - 2

GENERAL INFORMATION

2.1 National Templates, DOE Codes and Standards Coordinating Committee

2.2 Definitions and Glossary (pending)

General Information Appendix 2.1

National Templates, DOE Codes and Standards Coordinating Committee

The development and promulgation of codes and standards are essential to establish a market-receptive environment for commercial, hydrogen-based products and systems. For the past decade, the U.S. Department of Energy (DOE) has sponsored a national effort by government and industry to prepare, review, and promulgate hydrogen codes and standards needed to expedite hydrogen infrastructure development and to help enable the emergence of hydrogen as a significant energy carrier. The DOE has supported research and development needed to strengthen the scientific basis for technical requirements incorporated in national and international standards, codes, and regulations as well as the harmonization of these requirements that are essential for the safe use of hydrogen by consumers in the US and throughout the world.

Over the past three years, a national agenda for hydrogen codes and standards has emerged through a collaborative effort among DOE, industry, standards development organizations (SDO), and model code developers. This collaboration has enabled significant progress in the development of codes and standards for hydrogen applications. For example, provisions for hydrogen use are now included in the International Code Council's (ICC) International Building, Residential, Fire, Mechanical, and Fuel Gas model codes. Additional provisions, such as underground storage of liquid hydrogen and canopy storage of gaseous hydrogen will be incorporated in the 2006 edition of the ICC model codes and will further reduce the footprint of hydrogen fueling stations.

A key to the success of the national effort was the creation of "national templates" through which DOE, NREL, and the major SDOs and model code organizations coordinate the preparation of critical standards and codes for hydrogen technologies in vehicular and stationary applications (Figures A-1 and A-2, respectively). The national templates were created by consensus among the major SDOs and model code developers in workshops organized and facilitated by DOE. The SDOs and model code developers that are included in the national templates are the American National Standards Institute (ANSI), American Petroleum Institute (API), American Society of Mechanical Engineers (ASME), Compressed Gas Association (CGA), CSA America (CSA), Institute of Electrical Engineer and Electronics Engineers (IEEE), International Code Council (ICC), National Fire Protection Association (NFPA), Society of Automotive Engineers (SAE), and Underwriters Laboratory (UL). The DOE, Department of Transportation (DOT), Environmental Protection Agency (EPA), and the National Institute of Standards and Technology (NIST) are the federal agencies included in the templates. It is also important to note that state and local governments must incorporate standards and model codes in regulations for the standards and codes to be enforceable.

The national templates identify the key areas for which hydrogen standards and codes are required and the SDOs or model code developers that will lead and support the effort in each area. The templates provide an overall structure to facilitate collaboration and reduce duplicative effort. The structure provided by the templates is managed through the DOE Hydrogen Codes and Standards Coordinating Committee (HCSCC). Through monthly conference calls and quarterly meetings organized by NREL, the HCSCC provides a forum for the codes and standard community to keep participants aware of progress in implementing the templates and discuss issues and concerns that may arise. In addition to the organizations identified above, industry participants include the FreedomCAR and Fuel Partnership (DaimlerChrysler Corporation, Ford Motor Company, General Motors Corporation; BP America, Chevron Corporation, Exxon Mobil Corporation, Shell Hydrogen), Ballard Power Systems, General Electric, Plug Power, Stuart Energy, and UTC Fuel Cells. Participating industry associations include the Gas Technology Institute GTI), National Hydrogen Association (NHA), and the US Fuel Cell Council (USFCC).

An important part of implementing the national templates is to maintain an awareness of the status of and changes in hydrogen code and standards. To this end, the HCSCC maintains a matrix (posted at www.hydrogensafety.info) that lists codes and standards by application area and for each code and standard listed provides a brief description, technical contacts, and current status. Information about current codes and standards issues is also provided though the Hydrogen Safety Newsletter published monthly by the NHA and available at the same website as the matrix. The HCSCC has also created an interactive website (www.fuelcellstandards.com) that allows searching for information on codes and standards under several search criteria, including application and geographic region. The website also tracks activities in codes and standards and will eventually provide a one-stop site for information on codes and standards. To improve access to current hydrogen codes and standards, the DOE an NREL are working with ANSI to create hydrogen portal on ANSI's national standards network. The portal is intended to provide electronic access to key hydrogen standards and model codes, and ANSI is negotiating with the SDOs and model code developers included in the national templates to post and enable downloading of selected hydrogen standards and model codes.